

Laser Trepanning for Industrial Applications

Posted on September 15, 2018

Introduction

The continuing miniaturization of industrial products has increased the demand for precise holes in metals, ceramics, glass, polymers, and composite materials. Components used in aerospace engines, automotive fuel systems, medical instruments, electronic devices, and scientific sensors may require holes that are only a few micrometers wide. These holes must often possess controlled diameters, smooth walls, high aspect ratios, and carefully designed tapers. Conventional drilling becomes increasingly difficult under such conditions because small mechanical tools are fragile, experience rapid wear, and may damage brittle or delicate materials.

Laser drilling provides an alternative because it removes material without placing a physical cutting tool against the workpiece. A focused laser beam deposits energy in a small area, causing the material to melt, vaporize, or undergo ablation. The process can be digitally controlled and adapted to materials that are difficult to machine mechanically. However, simple laser drilling does not always produce an accurately shaped hole. Conventional percussion drilling, for example, frequently creates a hole that is wider at the entrance and narrower at the exit.

Laser trepanning addresses this limitation by moving a focused beam around the circumference of the desired hole. Instead of directing every pulse at one fixed position, the beam follows a circular or spiral path and gradually removes material from the hole boundary. This movement provides greater control over hole diameter, roundness, wall geometry, and taper. Ashkenasi et al. (2011) developed a rotating optical trepanning system in which beam focusing, displacement, and inclination could be adjusted to produce cylindrical, positively tapered, or negatively tapered holes.

Laser trepanning illustrates how advances in optics can improve industrial manufacturing. At the same time, developments in laser spectroscopy have expanded the role of lasers beyond machining. Field laser systems are now used to detect gases, monitor combustion, analyze the atmosphere, and investigate molecules in human breath. The Field Laser Applications in Industry and Research conference series has encouraged cooperation among academic researchers, instrument developers, and industrial users working in these areas.

This essay explains the operating principles of laser trepanning, examines the historical LMTB trepanning system, evaluates its industrial applications and limitations, and discusses the broader role of field laser technologies in research, environmental monitoring, medicine, and industrial process control.

What Is Laser Trepanning?

Laser trepanning is a drilling technique in which a focused laser beam travels around the perimeter of a hole. It may also be called laser core drilling because the beam cuts around a central portion of material rather than removing the entire area through a single stationary exposure.

The process usually begins by piercing the material or establishing a circular cutting path. The beam then rotates or scans along the required circumference. Repeated passes deepen the cut until the central core is removed and a complete through-hole is formed. In spiral trepanning, the laser may begin near the center and move outward in a spiral before continuing around the final diameter.

Laser trepanning differs from single-pulse and percussion drilling. Single-pulse drilling attempts to create a hole with one sufficiently energetic pulse. Percussion drilling applies several pulses to approximately the same location. Both methods can operate rapidly, but they provide less control over the final wall geometry. Trepanning takes additional time because the beam must follow a programmed path, yet it can produce larger and more accurately controlled openings.

Table 1

Comparison of Major Laser-Drilling Methods

Drilling Method	Basic Process	Main Advantages	Main Limitations
Single-pulse drilling	One high-energy pulse penetrates the workpiece	Very rapid and mechanically simple	Limited control over shape, taper, and wall quality
Percussion drilling	Repeated pulses strike approximately the same position	Fast production of small holes	May create recast material, irregular walls, and positive taper
Circular trepanning	The beam repeatedly follows the circumference of the hole	Better diameter, roundness, and taper control	Longer processing time and more complex beam steering
Spiral trepanning	The beam follows a spiral path before or during circumferential cutting	Controlled energy distribution and improved material removal	Requires accurate motion control and parameter optimization

The choice among these methods depends on the material, required diameter, thickness, production volume, and acceptable level of thermal damage. A manufacturer producing thousands of simple openings may prioritize speed, whereas an aerospace manufacturer producing cooling holes may place greater emphasis on taper, surface integrity, and repeatability.

Optical Principles of the LMTB Trepanning System

Laser- und Medizin-Technologie Berlin GmbH, commonly identified as LMTB, developed a rotating trepanning system intended to improve control over microhole geometry. The optical design reported by Ashkenasi et al. (2011) divided beam management into three main stages: focusing, displacement, and inclination.

Beam Focusing

The laser beam first passes through stationary focusing optics. A lens concentrates the optical energy into a small spot near the workpiece. The focal length influences the spot size, working distance, depth of focus, and achievable aspect ratio.

A strongly focused beam can produce a small spot and high energy density. However, the region in which the beam remains sufficiently narrow may also become shorter. A longer focal length can increase the Rayleigh range, allowing the beam to remain reasonably focused over a greater distance. This feature is important when drilling deep holes or working with thicker materials.

Focusing must be adjusted carefully because an incorrect focal position can enlarge the entrance, reduce penetration, or create an uneven energy distribution. The LMTB researchers therefore described “optimal focusing” as one of the principal requirements of an effective industrial trepanning system (Ashkenasi et al., 2011, p. 331).

Beam Displacement

After focusing, the converging beam is displaced parallel to its original optical axis. This displacement establishes the radius of the circular path. When the displaced optics rotate, the focused beam travels around the workpiece rather than remaining at one central point.

Increasing the displacement generally increases the diameter of the trepanned hole. The system can therefore modify hole diameter without moving the complete workpiece along a large circular trajectory. This optical method is especially valuable for small holes because the movement can be performed rapidly and with high precision.

Beam Inclination

The displaced beam then passes through an adjustable prism arrangement that introduces an inclination angle. The beam is directed back toward the optical axis at a selected angle before reaching the workpiece.

Beam inclination controls the relationship between the entrance and exit diameters. When the beam boundary is aligned approximately perpendicular to the workpiece surface, the system can produce a cylindrical or taper-free hole. A different inclination can create a positive or negative taper.

A positive taper means that the entrance is wider than the exit. A negative or reverse taper means that the exit is wider than the entrance. Although designers frequently attempt to minimize taper, some industrial components deliberately require tapered holes to control fluid flow, cooling, spray formation, or mechanical attachment.

Figure 1

Simplified Optical Path in a Laser Trepanning System

Laser source
↓
Stationary focusing lens
↓
Focused and converging beam
↓
Rotating displacement optics
↓
Beam moved parallel to the original axis
↓
Rotating inclination or prism optics
↓
Beam directed toward the selected circular path
↓
Workpiece
↓
Controlled cylindrical or tapered hole

Note. This original simplified diagram is based on the optical arrangement described by Ashkenasi et al. (2011).

The system may also move downward along the z-axis while drilling. This movement keeps the effective focal region closer to the advancing base of the hole and is particularly useful for achieving

high depth-to-diameter ratios.

Development of the LMTB Trepanning Systems

The 2011 study described several stages in the historical development of the LMTB technology. These models should be understood as the configurations documented at the time of publication rather than as a list of products confirmed to be commercially available today.

Type 1.0

Type 1.0 represented an early development stage. It provided circular beam displacement but did not permit an independently adjustable inclination angle. Ashkenasi et al. (2011) described its use in the cutting and drilling of glass with a nanosecond-pulsed laser operating at a wavelength of 532 nanometers.

Processing transparent material could begin from the rear surface. The focus was then moved upward through the glass. This method helped produce structures with reduced taper because the beam interaction could be managed along the thickness of the material.

Type 2.1

Type 2.1 allowed both beam displacement and inclination to be adjusted manually. Once the settings were selected, they remained fixed during processing. This stability made the system suitable for repeated manufacturing tasks in which many holes of the same diameter and geometry were required.

For example, a manufacturer could configure the system for cylindrical holes of a specified width and then use the same setting for a large production batch. Manual adjustment was less flexible than motorized control, but it could provide a reliable and comparatively straightforward arrangement.

Type 2.2

Type 2.2 introduced motorized control of the optical elements. Stepper-motor stages allowed the beam displacement and inclination to be changed during operation. This improvement enabled the system to modify the cutting width and taper without stopping the rotating optics.

According to the original specifications, type 2.X systems could work with several laser wavelengths and pulse durations. The reported drilling or cutting range was approximately 50 to 1,500 micrometers, although larger diameters were considered possible. The system could provide inclination angles from approximately -5 to $+5$ degrees and rotation speeds below 20,000

revolutions per minute, with 10,000 revolutions per minute identified as a typical operating point (Ashkenasi et al., 2011).

Type 3.1

Type 3.1 was described as being under development when the paper was published. Its proposed purpose was to measure the positions of the displacement and inclination optics while the system was operating.

Online position measurement was expected to simplify calibration, support long-term stability, and make integration into computer numerical control platforms easier. This concept is important because industrial production requires more than one successful laboratory demonstration. A system must maintain accuracy over extended use, detect deviations, and communicate with automated manufacturing equipment.

Table 2

Historical LMTB Trepanning Configurations Described in 2011

System	Primary Adjustment	Intended Capability
Type 1.0	Circular displacement without independently variable inclination	Cutting and drilling transparent materials such as glass
Type 2.1	Manual displacement and inclination	Stable repeated production after fixed adjustment
Type 2.2	Motorized displacement and inclination during operation	Flexible control of diameter and taper
Type 3.1	Proposed online optical-position measurement	Easier calibration, stability monitoring, and CNC integration

Experimental Performance and Hole Quality

Ashkenasi et al. (2011) tested the type 2.2 system with a Q-switched, diode-pumped laser. The arrangement could operate at 1,064 or 532 nanometers, and the researchers used optical coatings intended to minimize transmission losses.

The experiments examined repeated circular ablation patterns and through-holes in one-millimeter-thick aluminum nitride ceramic. Each hole was reproduced at least 25 times so that the researchers could evaluate consistency. Deviations in diameter and roundness remained within a few micrometers.

The reported cylindrical holes included diameters of approximately 240, 120, and 90 micrometers. The system also created negative-taper holes in which the entrance measured approximately 90 micrometers and the exit measured 110 micrometers. Another example had an entrance of approximately 100 micrometers and an exit of 140 micrometers.

The experimental processing strategy used approximately 60 seconds for each hole. The focal position was shifted downward in 100-micrometer steps during drilling to maintain effective energy delivery as the depth increased. The authors indicated that comparable quality could potentially be obtained in less time after further process optimization.

These findings demonstrated the central advantage of trepanning: the optical arrangement could intentionally control the entrance diameter, exit diameter, and taper rather than accepting the natural geometry produced by a stationary beam.

Important Laser and Process Parameters

Laser trepanning performance depends on the interaction of numerous variables. No single setting produces the best result for every material.

Laser Power and Pulse Energy

The power and energy per pulse must be high enough to remove material. Insufficient energy can cause incomplete penetration, while excessive energy may create a large heat-affected zone, cracks, recast layers, or an oversized entrance.

Pulse Duration

Pulse duration influences how energy is transferred into the workpiece. Nanosecond and millisecond pulses provide useful industrial processing rates but may allow more heat to spread into the surrounding material. Picosecond and femtosecond pulses deliver energy over much shorter periods and can reduce the amount of melting and thermal diffusion.

Ultrashort pulses are therefore attractive for high-precision micromachining. Nevertheless, they do not automatically eliminate defects. The final quality still depends on energy density, overlap, scanning trajectory, material properties, and removal of debris.

Wavelength

The workpiece must absorb sufficient laser energy at the selected wavelength. A wavelength suitable for a metal may not be optimal for glass, ceramics, or polymers. Optical coatings and beam-delivery components must also be compatible with the chosen wavelength.

Scanning Speed and Pulse Overlap

If the beam travels too quickly, the pulses may not overlap sufficiently to form a continuous cut. If it moves too slowly, excessive energy can accumulate, increasing melting and thermal damage. The pulse-repetition rate and rotational speed must therefore be coordinated.

Defocusing Distance

Changing the focal position alters the spot size and energy distribution. Research on titanium-alloy trepanning has shown that defocusing can substantially influence hole taper and outlet roundness. Wang et al. (2025) found that laser power, scanning speed, defocusing distance, and scan number affected different measures of microhole quality.

Number of Scans

A single circular pass may not penetrate a thick workpiece. Multiple scans gradually deepen the hole. Too few passes can leave an incomplete opening, while unnecessary repetitions increase processing time and heat input.

Modern optimization therefore treats laser trepanning as a multivariable process. Researchers may use designed experiments, statistical analysis, imaging, or machine-learning models to identify a useful operating window rather than changing one variable at a time.

Industrial Applications of Laser Trepanning

Aerospace Components

Aerospace engines require small cooling holes in turbine blades and related components. Air passing through these openings forms a cooling film that protects the metal from extreme operating temperatures. The diameter, angle, and taper of each opening affect airflow and cooling performance.

Laser trepanning is useful because turbine components are often made from hard, heat-resistant alloys that cause rapid mechanical-tool wear. Li et al. (2020) demonstrated that femtosecond spiral

trepanning could produce normal-taper, straight, and reverse-taper microholes by controlling the scanning path, energy distribution, and defocusing distance.

Automotive Fuel Injection

Fuel-injector nozzles contain carefully designed microholes that influence spray shape, atomization, combustion efficiency, and emissions. An irregular or poorly tapered hole can alter the fuel jet and reduce engine performance.

Trepanning allows manufacturers to control the opening geometry more precisely than a fixed beam. However, nozzle production also requires exceptionally smooth internal surfaces and minimal recast material. Laser processing may consequently be combined with electrical-discharge machining or finishing methods when one process alone cannot satisfy all requirements.

Electronics and Microdevices

Electronic components may require microvias, cooling apertures, sensor openings, and holes for electrical connections. Laser drilling is well suited to thin foils and delicate substrates because it is noncontact and digitally programmable.

Different hole patterns can be produced without manufacturing a separate physical drill for every diameter. This flexibility is useful in prototype development and in production lines that handle several component designs.

Ceramics and Glass

Ceramics possess valuable electrical, thermal, and wear-resistant properties, but they are brittle and difficult to machine mechanically. Glass can also crack when subjected to concentrated mechanical forces.

Laser trepanning can drill these materials without direct tool pressure. Careful selection of wavelength, focal position, pulse duration, and scanning strategy remains necessary because excessive thermal stress may still create fractures or edge damage.

Medical and Scientific Devices

Medical needles, filters, fluid-control components, laboratory chips, and miniature sensors may contain openings through which gases or liquids must pass. In these applications, a few micrometers of dimensional error can influence flow or measurement accuracy.

Laser trepanning can support the fabrication of such features, but medical applications require strict

control of contamination, surface finish, and repeatability. The machining process must therefore be followed by inspection and, where necessary, cleaning or post-processing.

Benefits and Limitations

The most important advantage of laser trepanning is geometric control. The beam path can be adjusted to change diameter, taper, and roundness. Because the process is noncontact, there is no cutting tool that becomes blunt or breaks inside a miniature hole.

The same optical system can also process several materials and dimensions after its parameters are changed. This adaptability reduces the need to manufacture specialized mechanical drills for every design.

Nevertheless, laser trepanning has limitations. It is often slower than percussion drilling because the beam must complete several circular or spiral passes. The optical and motion systems are also more complicated. Misalignment, vibration, contamination of protective optics, and calibration errors can reduce accuracy.

Thermal defects remain possible, particularly with longer pulses. These defects include recast layers, microcracks, dross, changes in material structure, and heat-affected zones. Debris may also accumulate inside deep holes and interfere with later pulses.

An industrial system must therefore balance quality and productivity. Extremely slow processing may create excellent laboratory specimens but remain economically unsuitable for mass production. Conversely, rapid drilling has little value when excessive defects cause component rejection.

Field Laser Applications in Industry and Research

Industrial laser technology includes much more than material removal. The Field Laser Applications in Industry and Research, or FLAIR, conference series was created to connect researchers who develop laser-detection instruments with specialists who need measurements in real working environments.

Kerstel et al. (2017) emphasized the importance of cooperation among academic researchers, industrial laboratories, instrument developers, and users. This interdisciplinary approach is necessary because a highly sensitive laboratory instrument may not function successfully in a factory, hospital, aircraft, or outdoor monitoring station. Field systems must cope with vibration, temperature variation, dust, humidity, changing gas mixtures, and limited maintenance.

The FLAIR research community has addressed applications such as atmospheric monitoring, industrial process control, combustion analysis, biomedical sensing, and selective molecular detection. These fields share a need to identify small concentrations of a target substance among many interfering

compounds.

Laser Spectroscopy for Breath Analysis

Human breath contains numerous gases and volatile compounds produced by metabolism, diet, environmental exposure, and disease processes. Carbon dioxide, nitric oxide, acetone, ammonia, methane, and other molecules can potentially provide information about health.

Traditional laboratory analysis may require collecting a sample and transporting it to a centralized instrument. Laser spectroscopy offers the possibility of faster measurements because a laser can be tuned to wavelengths absorbed by a selected molecule.

Wang and Sahay (2009) described laser-based breath analysis as potentially “noninvasive, real-time, and point-of-care” (p. 8230). Their review identified several techniques that had been applied to breath biomarkers, including tunable diode-laser absorption spectroscopy, cavity ring-down spectroscopy, photoacoustic spectroscopy, and optical-frequency-comb spectroscopy.

Breath analysis remains technically challenging. Water vapor and carbon dioxide can interfere with weak signals, and the relationship between a breath compound and a disease is not always specific. A reliable medical test requires validated sampling methods, reference ranges, and clinical evidence. Nevertheless, laser spectroscopy offers an important platform for studying breath chemistry without invasive sample collection.

Optical Frequency Combs and Broadband Detection

An optical frequency comb produces many precisely spaced spectral lines. It can be compared to a ruler for measuring optical frequencies. Instead of examining only one narrow absorption feature, a frequency-comb system can measure several features across a wider spectral region.

Khodabakhsh et al. (2017) demonstrated mid-infrared Vernier spectroscopy using a doubly resonant optical parametric oscillator. Techniques of this type are valuable because many molecules possess strong and distinctive absorption patterns in the mid-infrared region.

Broadband measurement can improve the identification of gas mixtures because the instrument observes several molecular fingerprints simultaneously. However, frequency-comb systems may involve complex optical alignment, data analysis, and cost. Field deployment therefore requires compact and stable designs.

Cavity Ring-Down and Photoacoustic Methods

Cavity ring-down spectroscopy increases sensitivity by placing the sample inside an optical cavity formed by highly reflective mirrors. Light travels through the gas repeatedly, producing an effective absorption path much longer than the physical size of the instrument.

Instead of relying only on the absolute intensity of the transmitted beam, the system measures how rapidly the light decays after the input is interrupted. Westberg and Wysocki (2017) combined cavity ring-down spectroscopy with Faraday-rotation measurements for oxygen detection. Their experiment achieved an oxygen-detection limit of 160 parts per billion after 100 seconds of averaging.

Photoacoustic spectroscopy uses a different principle. Modulated laser energy is absorbed by the target molecules and converted into periodic heating. The resulting pressure waves can be measured as sound. Quartz-enhanced photoacoustic spectroscopy uses a quartz tuning fork as a sensitive acoustic detector.

Mordmüller et al. (2017) examined electrical co-excitation in quartz-enhanced photoacoustic measurements under changing background-gas conditions. Such research addresses a practical field problem: a sensor may perform well in a stable laboratory mixture but respond differently when the composition of the surrounding gas changes.

Atmospheric and Combustion Monitoring

Laser spectroscopy can detect pollutants, greenhouse gases, combustion products, and industrial leaks. Selective measurements of methane, carbon monoxide, carbon dioxide, nitrogen oxides, formaldehyde, and water vapor can support environmental research and process control.

In combustion systems, rapid measurements allow researchers to observe chemical changes while the process is occurring. Engineers can use these data to evaluate fuel efficiency, temperature, reaction pathways, and pollutant formation.

In atmospheric science, laser instruments may be installed on towers, vehicles, aircraft, or portable platforms. They can monitor spatial and temporal changes that would be missed by infrequent sample collection. However, outdoor systems must remain accurate despite changing pressure, temperature, humidity, and particle concentrations.

The Importance of Collaboration

Both laser trepanning and field spectroscopy demonstrate why cooperation between industry and academic research is essential. Researchers may develop optical principles and mathematical models, but industrial partners identify the practical requirements that determine whether a

technology can be used in production.

For laser trepanning, these requirements include speed, reliability, calibration, vibration control, integration with CNC equipment, and automated quality inspection. For field spectroscopy, they include portability, selectivity, resistance to environmental changes, simple maintenance, and clear interpretation of measurement results.

Scientific conferences, peer-reviewed publications, technical boards, sponsors, and collaborative projects allow knowledge to move among these groups. Such cooperation prevents advanced technologies from remaining isolated laboratory demonstrations.

Future Development

Future laser-trepanning systems are likely to include more automated monitoring and closed-loop control. Cameras, optical sensors, acoustic signals, plasma-emission measurements, and machine-learning models may be used to estimate hole depth or identify defects during processing.

Instead of applying fixed parameters to every component, an intelligent system could adjust laser power, focus, scan speed, or gas flow in response to real-time measurements. This would improve consistency when small variations occur in material thickness, surface condition, or absorption.

Ultrashort-pulse sources may further reduce thermal damage, while faster scanners and higher repetition rates may improve productivity. Hybrid approaches may combine lasers with water jets, electrical-discharge machining, or finishing processes to obtain the advantages of several technologies.

Field spectroscopy is also moving toward smaller and more integrated instruments. Advances in semiconductor lasers, optical frequency combs, detectors, fiber systems, and data processing may support portable sensors capable of identifying several gases at once.

The central challenge in both areas is the same: precision must be combined with reliability, affordability, and ease of use. A technically impressive system will have limited industrial value when it requires constant alignment or specialist attention.

Conclusion

Laser trepanning is an important micromachining technique for producing controlled holes in materials that are difficult to process mechanically. By separating beam control into focusing, displacement, and inclination, the LMTB system demonstrated how optical design can regulate hole diameter and taper.

The historical development from fixed optics to manually adjustable, motorized, and proposed online-

measurement configurations reflected the movement from laboratory experimentation toward automated industrial production. Experimental results in aluminum nitride ceramic showed that the system could reproduce cylindrical and negatively tapered holes with dimensional deviations of only a few micrometers.

Laser trepanning offers valuable benefits for aerospace cooling holes, automotive fuel nozzles, electronics, ceramics, glass, and medical devices. Its limitations include processing time, optical complexity, calibration requirements, and the possibility of thermal defects. Careful optimization of pulse duration, energy, wavelength, scan speed, focus, and number of passes is therefore necessary.

The broader field of laser applications extends from machining to molecular detection. Research presented through the FLAIR community demonstrates the use of lasers for breath analysis, atmospheric monitoring, combustion research, industrial control, and trace-gas sensing. Optical frequency combs, cavity ring-down methods, and photoacoustic techniques can detect molecular signals that would otherwise be difficult to measure.

Together, these developments show that lasers are not merely sources of concentrated energy. They are adaptable scientific and industrial tools that can cut, drill, measure, detect, and analyze with exceptional precision. Their future value will depend on continued cooperation between optical scientists, engineers, manufacturers, medical researchers, environmental specialists, and end users.

References

- Ashkenasi, D., Kaszemeikat, T., Mueller, N., Dietrich, R., Eichler, H. J., & Illing, G. (2011). Laser trepanning for industrial applications. *Physics Procedia*, 12, 323–331. doi: 10.1016/j.phpro.2011.03.140
- Kerstel, E., D'Amato, F., & Fried, A. (2017). Field laser applications in industry and research. *Applied Physics B*, 123, Article 250. doi: 10.1007/s00340-017-6827-3
- Khodabakhsh, A., Rutkowski, L., Morville, J., & Foltynowicz, A. (2017). Mid-infrared continuous-filtering Vernier spectroscopy using a doubly resonant optical parametric oscillator. *Applied Physics B*, 123, Article 210. doi: 10.1007/s00340-017-6781-0
- Li, F., Feng, G., Yang, X., Li, X., Ma, G., & Lu, C. (2020). Research on microhole processing technology based on the femtosecond-laser spiral trepanning method. *Applied Sciences*, 10(21), Article 7508. doi: 10.3390/app10217508
- Mordmüller, M., Schade, W., & Willer, U. (2017). QEPAS with electrical co-excitation for photoacoustic measurements in fluctuating background gases. *Applied Physics B*, 123, Article 224. doi: 10.1007/s00340-017-6799-3
- Schulz, W., Eppelt, U., & Poprawe, R. (2013). Review on laser drilling I: Fundamentals, modeling, and

simulation. *Journal of Laser Applications*, 25(1), Article 012006. doi: 10.2351/1.4773837

Wang, C., & Sahay, P. (2009). Breath analysis using laser spectroscopic techniques: Breath biomarkers, spectral fingerprints, and detection limits. *Sensors*, 9(10), 8230–8262. doi: 10.3390/s91008230

Wang, L., Rong, Y., Xu, L., Wu, C., & Xia, K. (2025). Process optimization on trepanning drilling in titanium alloy using a picosecond laser via an orthogonal experiment. *Micromachines*, 16(8), Article 846. doi: 10.3390/mi16080846

Westberg, J., & Wysocki, G. (2017). Cavity ring-down Faraday rotation spectroscopy for oxygen detection. *Applied Physics B*, 123, Article 168. doi: 10.1007/s00340-017-6743-6